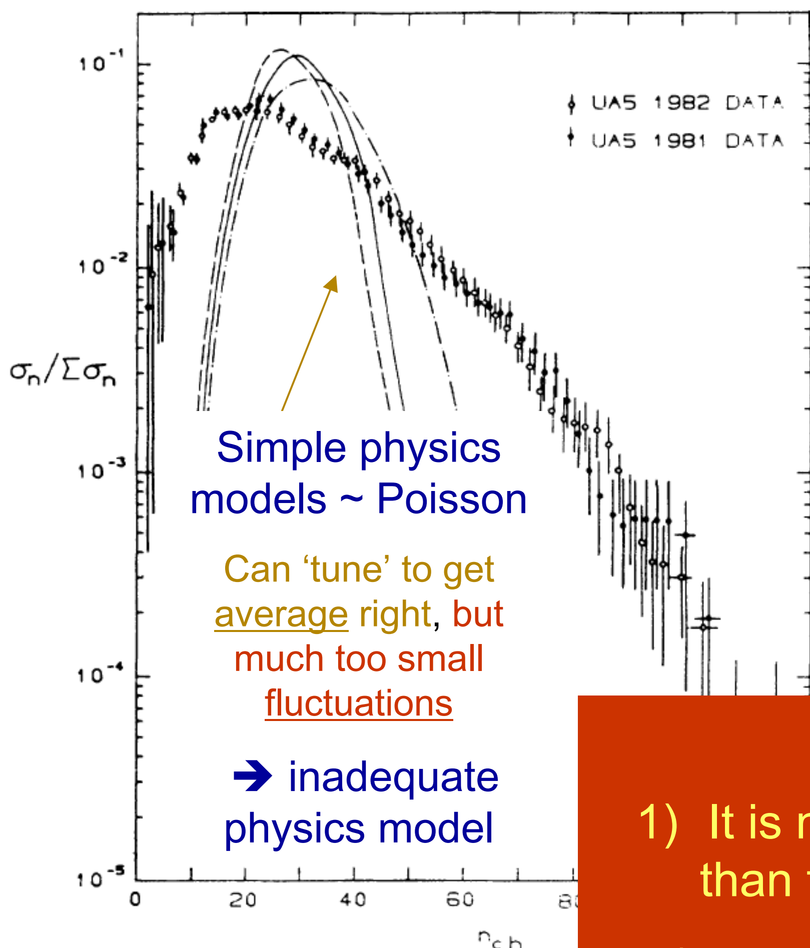
Terascale Meeting, U of Oregon, Eugene, February 2009

# Modeling the Underlying Event

Peter Skands
Theoretical Physics, Fermilab

# Models – Classic Example

UA5 @ 540 GeV, single pp, charged multiplicity in minimum-bias events

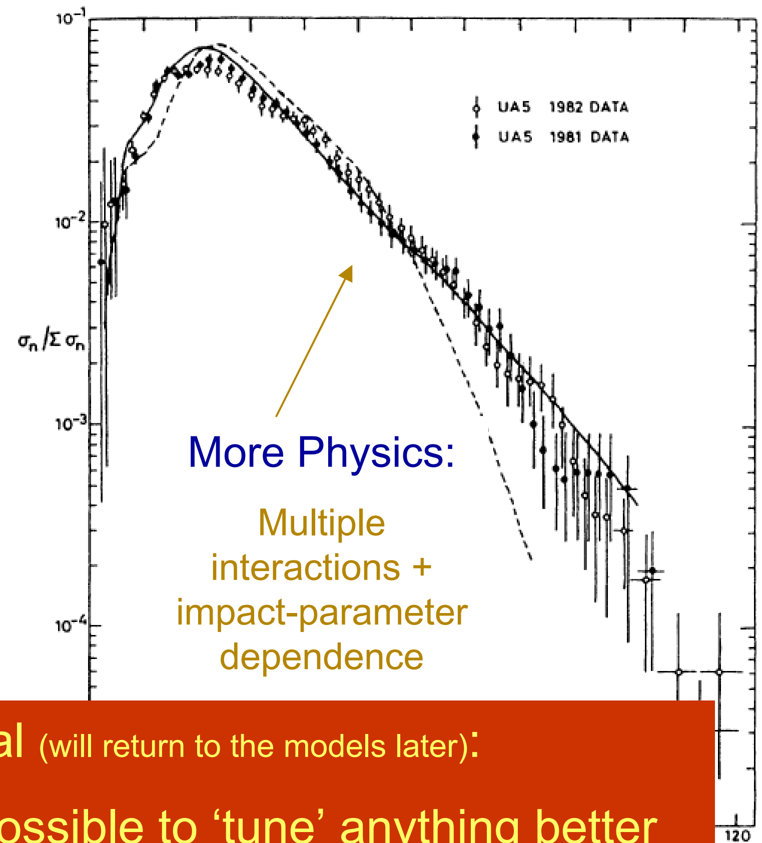



Simple physics models ~ Poisson

Can 'tune' to get average right, but much too small fluctuations

➔ inadequate physics model

FIG. 3. Charged-multiplicity distributio[…] results (Ref. 32) vs simple models: dashed […] cluding hard scatterings, dash-dotted also i[…] final-state radiation.




More Physics:

Multiple interactions + impact-parameter dependence

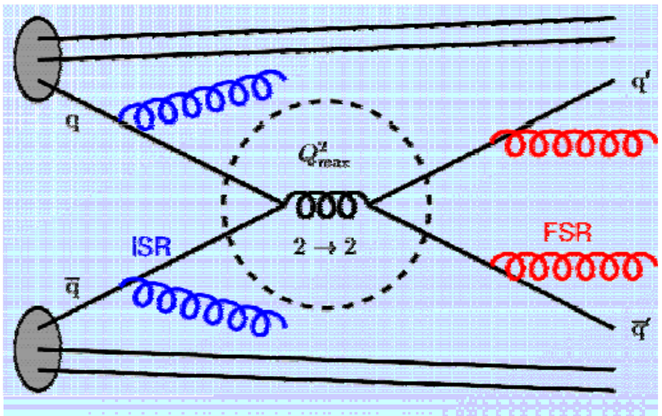
[…]eV, UA5 […]riable im- […]tribution; dashed line, with fix impact parameter [i.e., $O_0(b)$].

**Moral** (will return to the models later):

1) It is not possible to 'tune' anything better than the underlying physics model allows

2) Failure of a physically motivated model usually points to more, interesting physics

# Monte Carlo Philosophy




- Calculate Everything: **solve QCD** → requires compromise
  - Improve Born-level perturbation theory, by including the 'most significant' corrections → complete events → any observable you want

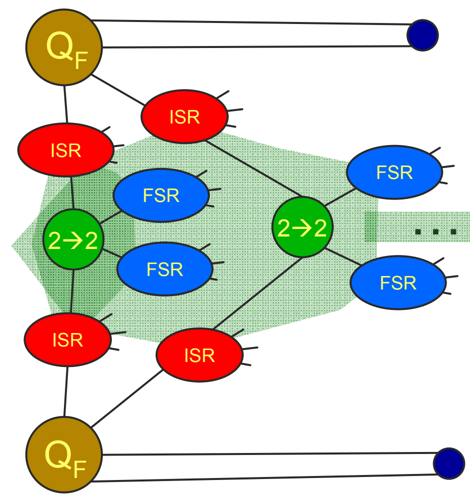
| | | |
|---|---|---|
| *1. Parton Showers* | | *1. Soft/Collinear Logarithms* |
| *2. Matching* | roughly | *2. Finite Terms, "K"-factors* |
| *3. Hadronisation* | | *3. Power Corrections (more if not IR safe)* |
| *4. The Underlying Event* | | *4. ?* |

(+ many other ingredients: resonance decays, beam remnants, Bose-Einstein, …)

Asking for complete events is a tall order …

# Additional Sources of Particle Production

- ► Starting point: matrix element + parton shower
  - hard parton-parton scattering
    - (normally 2→2 in MC)
  - + bremsstrahlung associated with it
    - → 2→n in (improved) LL approximation




$Q_F >> \Lambda_{QCD}$

► But hadrons are not elementary

► + QCD diverges at low $p_T$

→ multiple <u>perturbative</u> parton-parton collisions

e.g. 4→4, 3→ 3, 3→2

Underlying Event has perturbative part!

► No factorization theorem

→ Herwig++, Pythia, Sherpa: MPI models

# Additional Sources of Particle Production

$Q_F >> \Lambda_{QCD}$

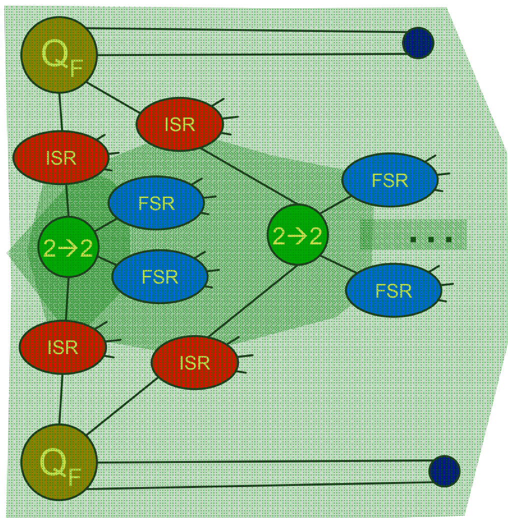
ME+ISR/FSR

+ perturbative MPI

+

Stuff at

$Q_F \sim \Lambda_{QCD}$




Need-to-know issues for IR sensitive quantities (e.g., $N_{ch}$)

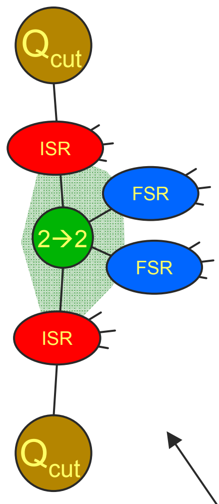
- Hadronization
- Remnants from the incoming beams
- Additional (non-perturbative / collective) phenomena?
  - Bose-Einstein Correlations
  - Non-perturbative gluon exchanges / color reconnections ?
  - String-string interactions / collective multi-string effects ?
  - “Plasma” effects?
  - Interactions with “background” vacuum, remnants, or active medium?

# Naming Conventions

See also **Tevatron-for-LHC Report of the QCD Working Group, hep-ph/0610012**

- Many nomenclatures being used.
  - Not without ambiguity. I use:

Some freedom in how much particle production is ascribed to each: "hard" vs "soft" models

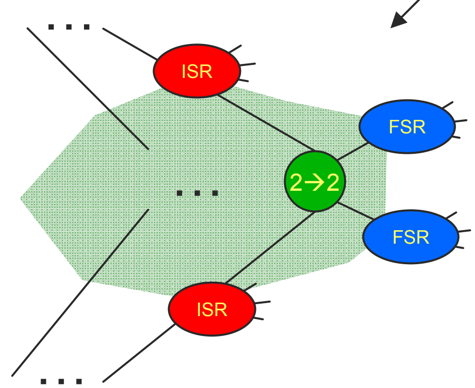



Primary

Interaction

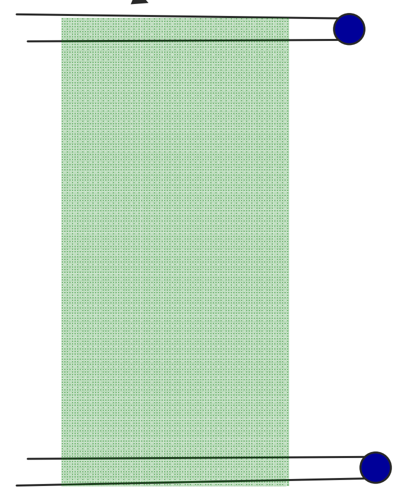
(~ trigger)

Inelastic, non-diffractive




Underlying

Event



Beam

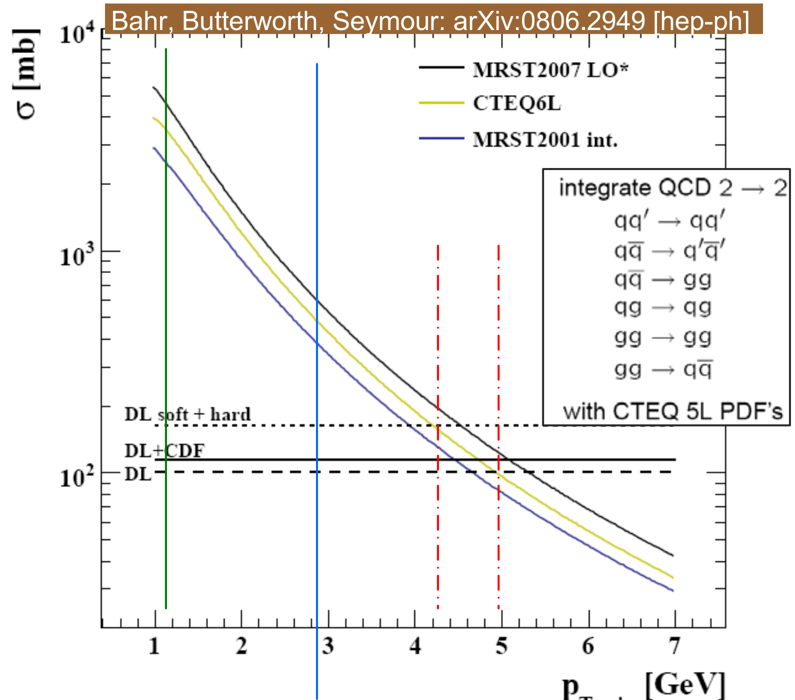
Remnants

Note: each is colored ➔ Not possible to separate clearly at hadron level

# Why Perturbative MPI?

- ► Analogue: Resummation of multiple bremsstrahlung emissions
  - Divergent σ for one emission (X + jet, fixed-order)
  - ➔ Finite σ for divergent number of jets (X + jets, infinite-order)
    - N(jets) rendered finite by finite perturbative resolution = parton shower cutoff

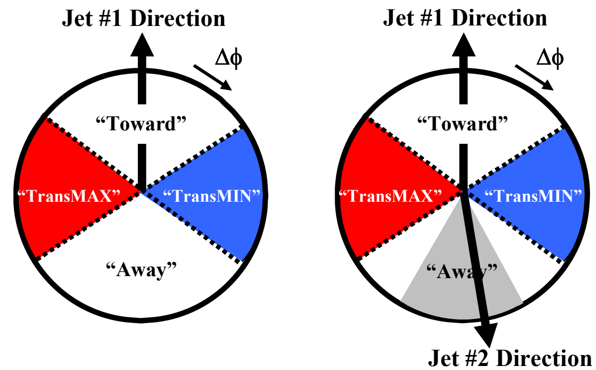
- ► (Resummation of) Multiple Perturbative Interactions
  - Divergent σ for one interaction (fixed-order)
  - ➔ Finite σ for divergent number of interactions (infinite-order)
    - N(jets) rendered finite by finite perturbative resolution = color-screening cutoff ($E_{cm}$-dependent, but large uncert)




Saturation? Current models need MPI IR cutoff > PS IR cutoff

# Why Perturbative MPI?

- + Experimental investigations (AFS, CDF)
  - Find pairwise balanced minijets,
  - Evidence for "lumpy" components in "transverse" regions
  - But that overview should be given by an experimentalist




- Here will focus on
  - Given that these are the models used by Tevatron and LHC experiments (and for pp at RHIC), what are their properties?
  - What are they missing?
- Especially in low-x context
  - → discussion session

NB: Herwig: no MPI.

Here will talk about Jimmy/Herwig++

# How many?

- The interaction cross section

$$\frac{\mathrm{d}\sigma_{2j}}{\mathrm{d}p_\perp^2} = \sum_{i,j,k} \int \mathrm{d}x_1 \int \mathrm{d}x_2 \int \mathrm{d}\hat{t}\; f_i(x_1,\mu_F^2)\, f_j(x_2,\mu_F^2)\, \frac{\mathrm{d}\hat{\sigma}_{ij\to kl}}{\mathrm{d}\hat{t}}\, \delta\!\left(p_\perp^2 - \frac{\hat{t}\hat{u}}{\hat{s}}\right) \propto \frac{1}{p_{\perp\min}^2}$$

With constant $\alpha_s$, neglecting $x$ integrals

  - … is an inclusive number.

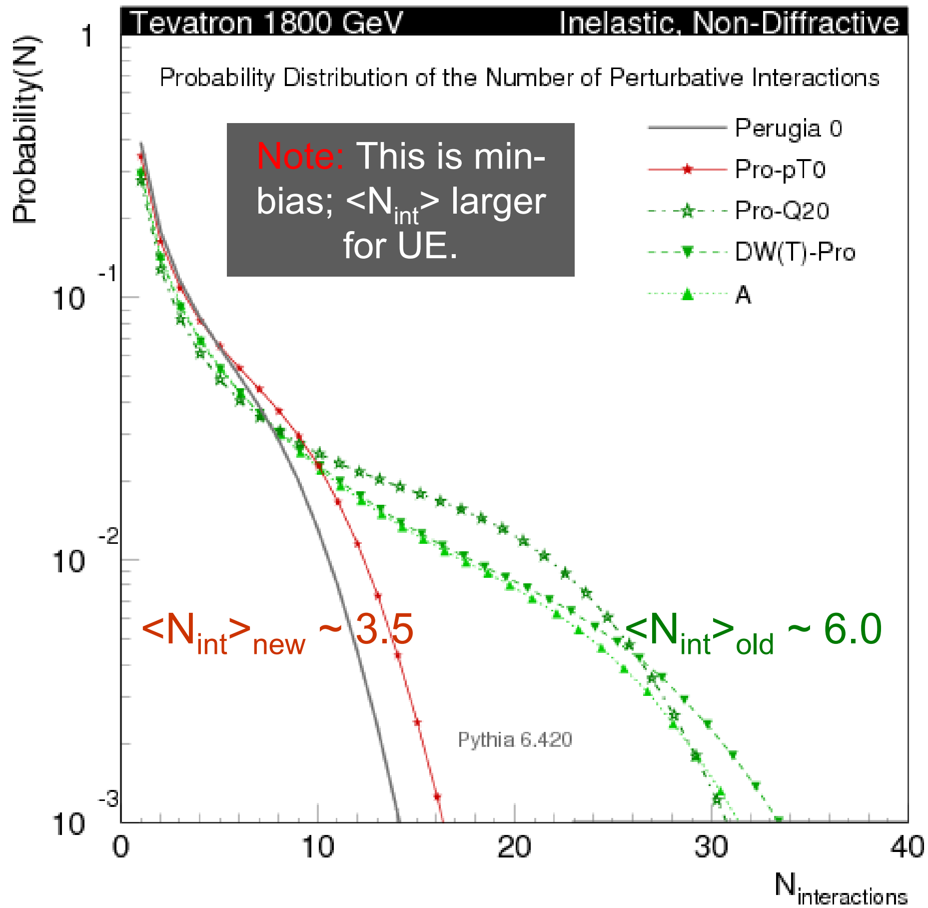
- … so an event with $n$ interactions …
  - … counts $n$ times in $\sigma_{2j}$ but only once in $\sigma_{tot}$

$$\langle n\rangle(p_{\perp\min}) = \frac{\sigma_{2j}(p_{\perp\min})}{\sigma_{\mathrm{tot}}} \Longleftrightarrow \mathcal{P}_n(p_{\perp\min}) = [\langle n\rangle(p_{\perp\min})]^n\, \frac{\exp\left[-\langle n\rangle(p_{\perp\min})\right]}{n!}$$

- Poisson only exact if the individual interactions are completely independent, so will be modified in real life
  - **Herwig** starts directly from Poisson → $n$, but includes vetos if (E,p) violated.
  - **Pythia** uses a transverse-momentum ordered Sudakov formalism, interleaved with the shower evolution ~ resummation. (E,p) explicitly conserved at each step.

# How many?

► Different Cocktails ➔ Probability distribution of $N_{MPI}$




Not necessary to believe in these particular numbers.

But good to know this is what is obtained with out-of-the-box MC models

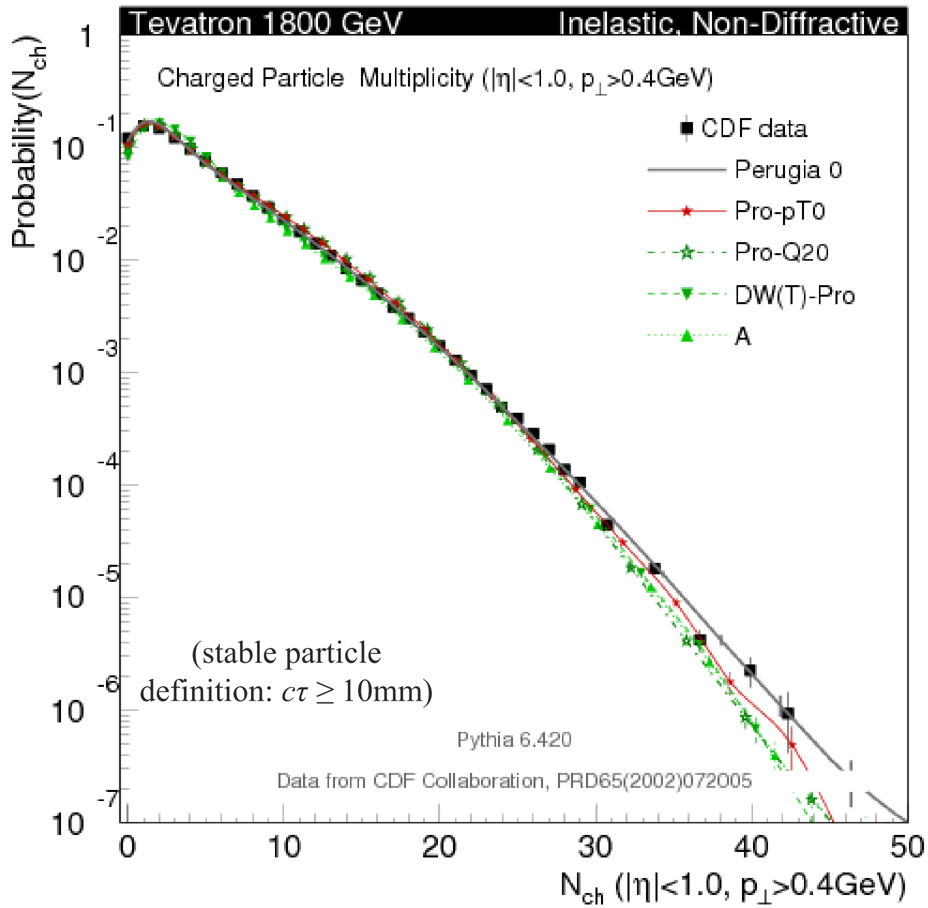
**Important Difference:**

Old model had no showers off MPI

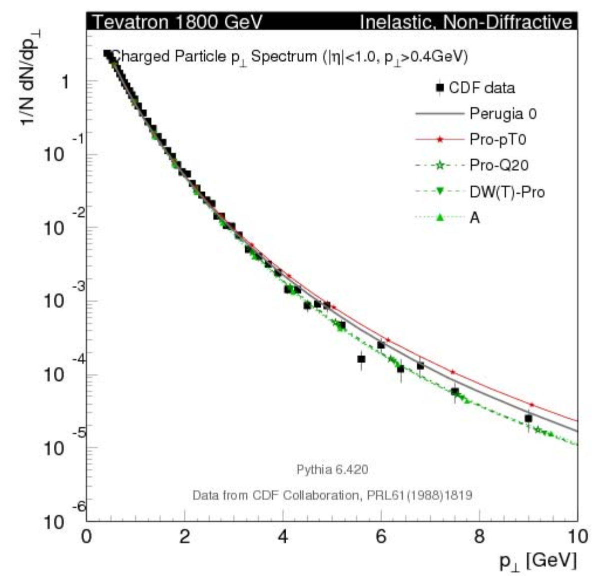
Buttar et al., Les Houches SMH Proceedings (2007) **arXiv:0803.0678** [hep-ph]
More plots collected at `http://home.fnal.gov/~skands/leshouches-plots/`

# Different Cocktails?

- Observed charged particle multiplicity




Moral: vastly different cocktails can give similar answers




Buttar et al., Les Houches SMH Proceedings (2007) **arXiv:0803.0678** [hep-ph]
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# Impact Parameter

- Impact parameter: central vs. peripheral collisions

All models currently assume f(x,b) = f(x) g(b)

  - Obviously not the final word.

- Large fluctuations → g(b) needs to be "lumpy"

Large difference between peripheral and central

"No" UE in peripheral collisions (low multiplicity)

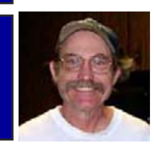
"Jet pedestal" effect

"Saturated" UE in central collisions (high multiplicity)

**Pythia: default: double gaussian: "hard core" (valence lumps?)**

$$\rho(r) \propto \frac{1-\beta}{a_1^3}\exp\left\{-\frac{r^2}{a_1^2}\right\} + \frac{\beta}{a_2^3}\exp\left\{-\frac{r^2}{a_2^2}\right\}$$

Core size $a_2/a_1 = 0.5$
Contains fraction $\beta = 0.4$



**Herwig: EM form factor, but width rescaled to smaller radius**

$$G_{\bar{p}}(\mathbf{b}) = G_p(\mathbf{b}) = \int \frac{d^2\mathbf{k}}{2\pi}\frac{e^{i\mathbf{k}\cdot\mathbf{b}}}{(1+\mathbf{k}^2/\mu^2)^2}$$

$\mu_{ep} = 0.7\ \mathrm{GeV}^2 \rightarrow \mu = 1.5\ \mathrm{GeV}^2$

# Multi-parton pdfs

**Herwig**

Snapshot of proton: re-use 1-parton inclusive f(x)

Subsequently impose (E,p) cons by vetoing events that violate it.

**Pythia**

1-parton inclusive f(x) = pdf for “trigger” scattering

Multi-parton pdfs explicitly constructed, respecting flavour and momentum sum rules

**quarks**

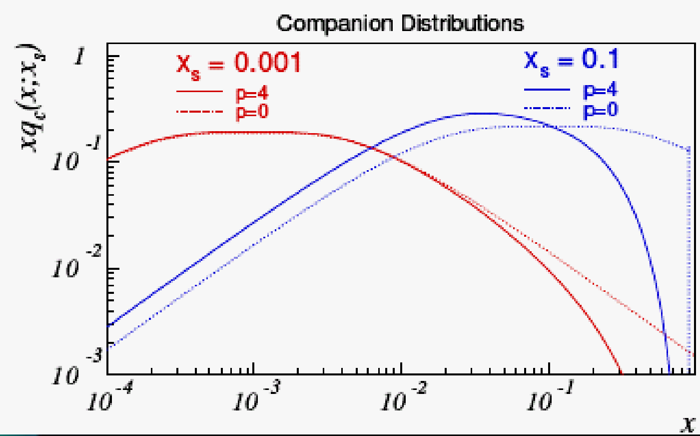
$$q_{fn}(x) = \frac{1}{X}\left[\frac{N^{\mathrm{val}}_{fn}}{N^{\mathrm{val}}_{f0}}\, q^{\mathrm{val}}_{f0}\left(\frac{x}{X}, Q^2\right) + a\, q^{\mathrm{sea}}_{f0}\left(\frac{x}{X}, Q^2\right) + \sum_j q^{\mathrm{cmp}_j}_{f0}\left(\frac{x}{X}; x_{s_j}\right)\right]$$

$$q^{\mathrm{cmp}}_{f0}(x; x_s) = C\, \frac{\tilde{g}(x+x_s)}{x+x_s}\, P_{g\to q_f \bar{q}_f}\left(\frac{x_s}{x+x_s}\right) \quad ; \quad \left(\int_0^{1-x_s} q^{\mathrm{cmp}}_{f0}(x; x_s)\,\mathrm{d}x = 1\right)$$

**gluons**

$$g_n(x) = \frac{a}{X}\, g_0\left(\frac{x}{X}, Q^2\right)$$

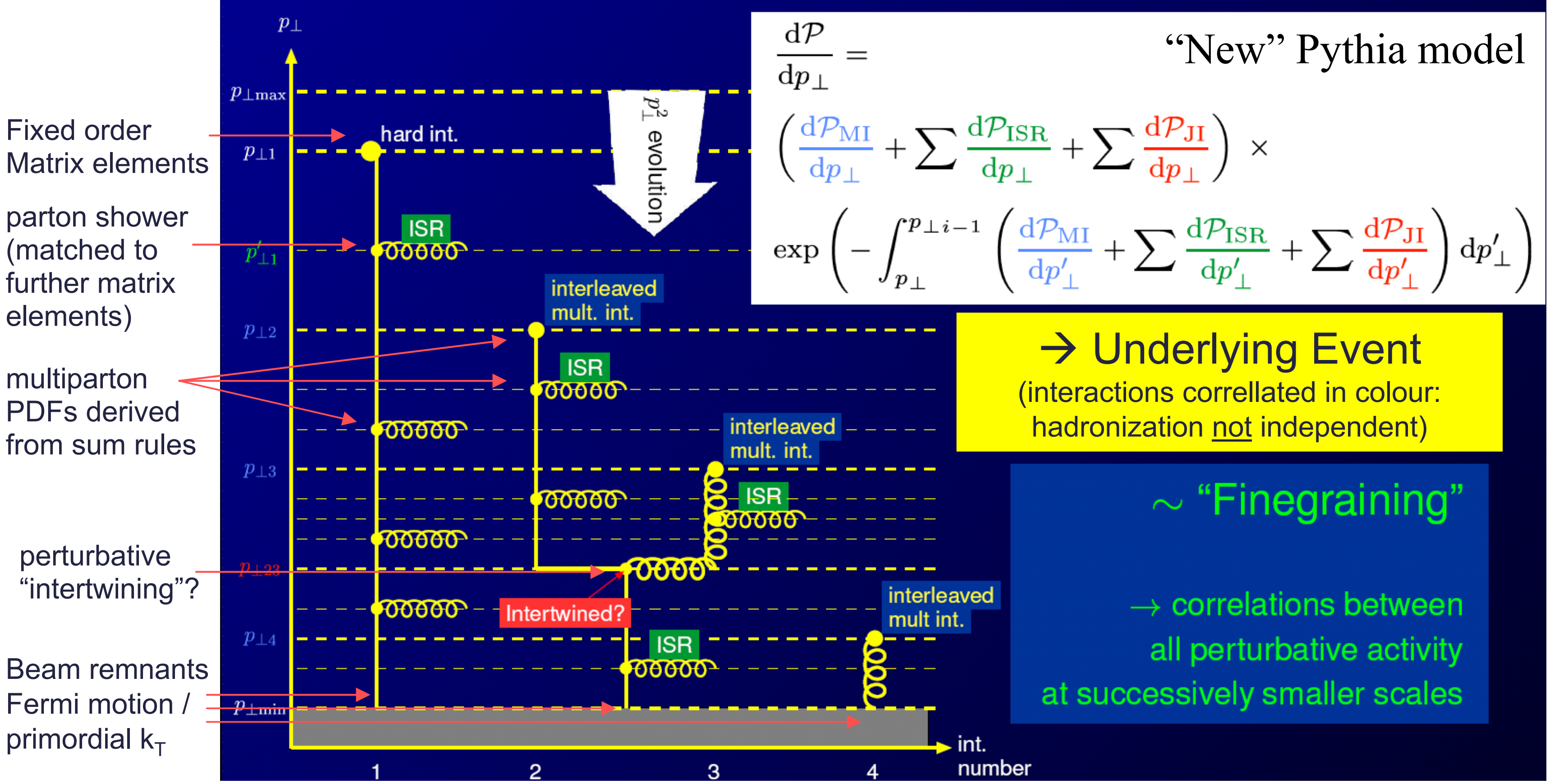
$$a = \frac{1 - \sum_f N^{\mathrm{val}}_{fn}\langle x^{\mathrm{val}}_{f0}\rangle - \sum_{f,j}\langle x^{\mathrm{cmp}_j}_{f0}\rangle}{1 - \sum_f N^{\mathrm{val}}_{f0}\langle x^{\mathrm{val}}_{f0}\rangle}$$



# Interleaved Evolution

Pythia

The new picture: start at the most inclusive level, $2 \to 2$.
Add exclusivity progressively by evolving *everything* downwards.

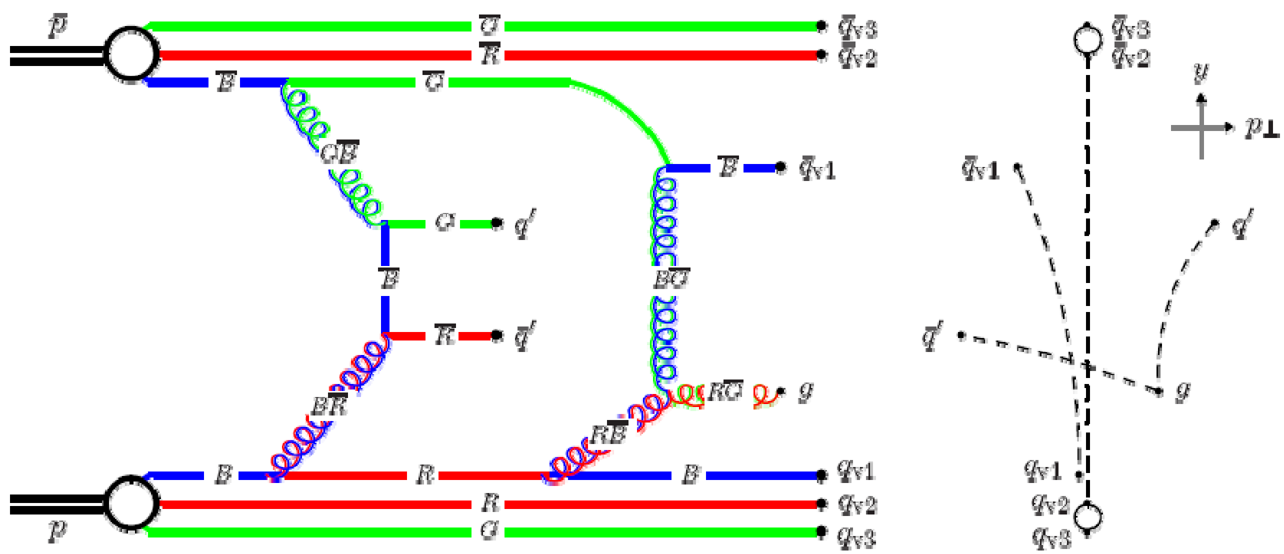



Sjöstrand, PS; JHEP03(2004)053, EPJC39(2005)129

# Underlying Event and Color

► The colour flow determines the hadronizing string topology

- Each MPI, even when soft, is a color spark
- Final distributions <u>crucially</u> depend on color space




Note: this just color **connections**, then there may be color **re-connections** too

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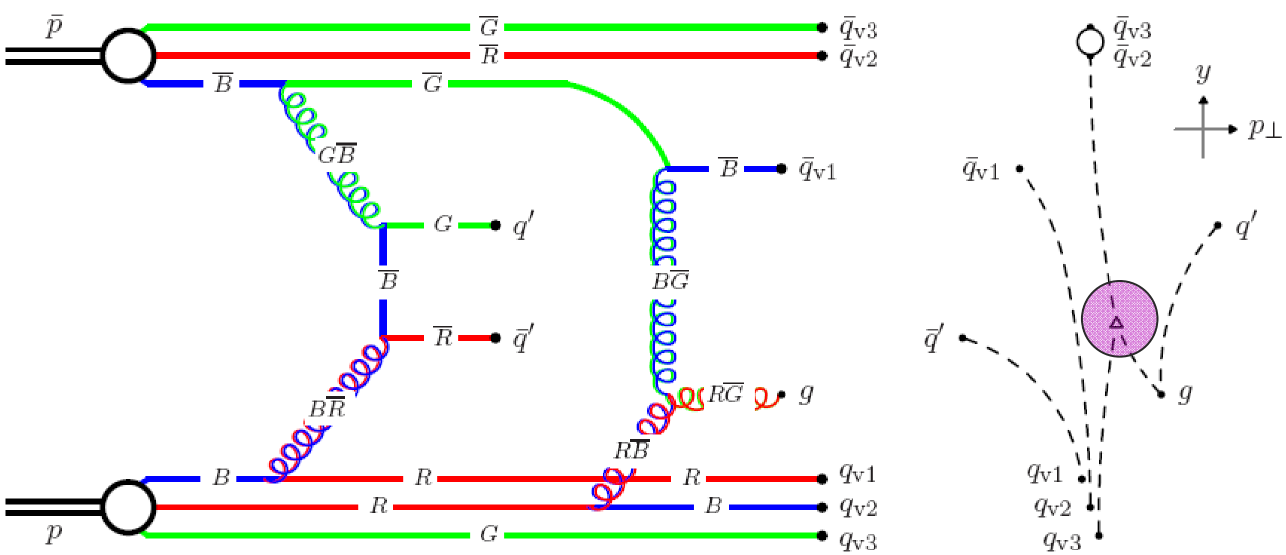



Note: this just color **connections**, then there may be color **re-connections** too

# Color Connections

Pythia

- ‘Old’ Model
  - Set up color flow for hard interaction + shower as usual
  - Treat MPI as separate color singlet systems – alternatively attach gluons where they would cause the smallest ‘kinks’
- ‘New’ Model
  - ‘Random’
  - Rapidity-ordered (connect systems along rapidity chain)
  - Lambda-optimized (cheating)

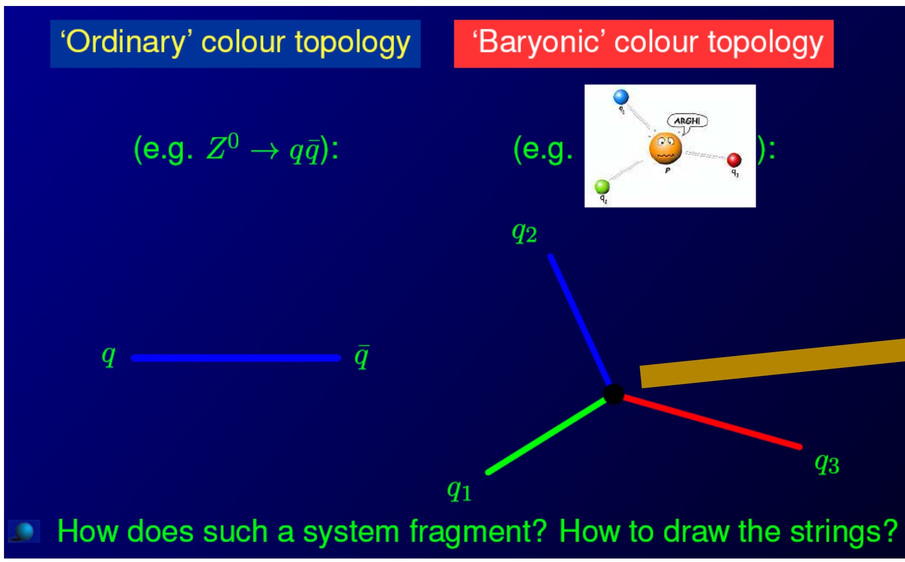
Herwig

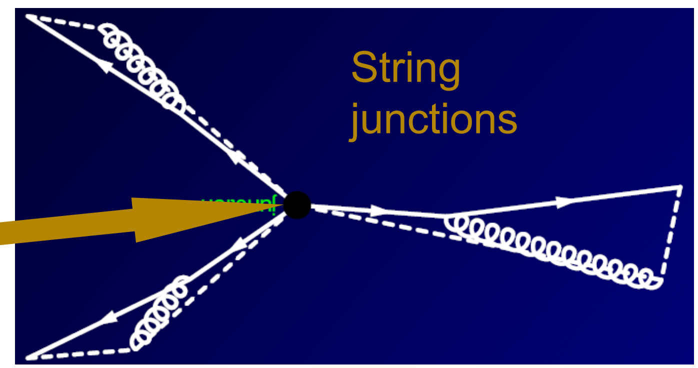
- ‘Random’

# Baryonic String Topologies

Pythia

- Original Lund string: leading-color (triplet-antitriplet) connections
  - → "Mesonic" description
  - Baryon number violation (or a resolved baryon number in your beam) ➔ explicit epsilon tensor in color space. Then what?



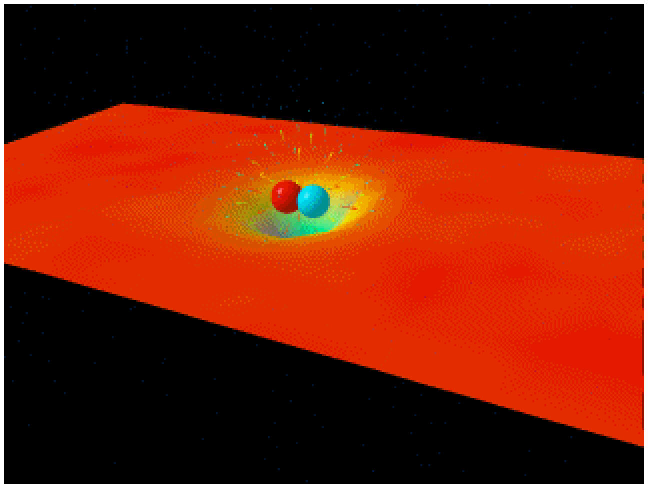

Sjöstrand & PS : Nucl.Phys.B659(2003)243, JHEP03(2004)053

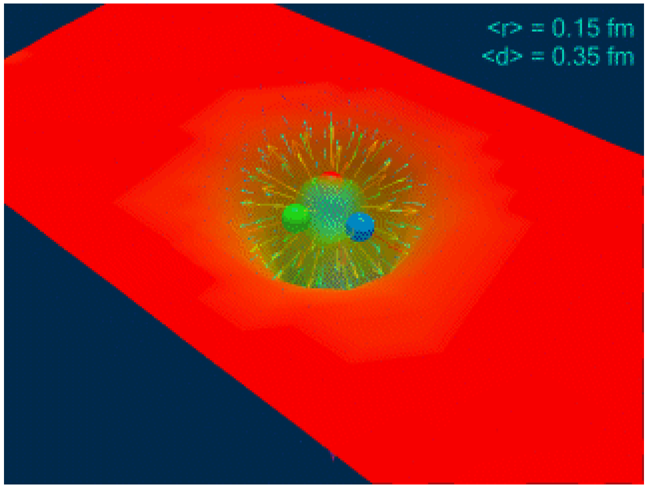
- Perturbative Triplets → String endpoints
- Perturbative Octets → Transverse kinks
- Perturbative Epsilon tensors → String junctions

# Baryonic String Topologies

- ► Lattice simulation of mesonic and baryonic configurations

Simulation from
D. B. Leinweber, hep-lat/0004025



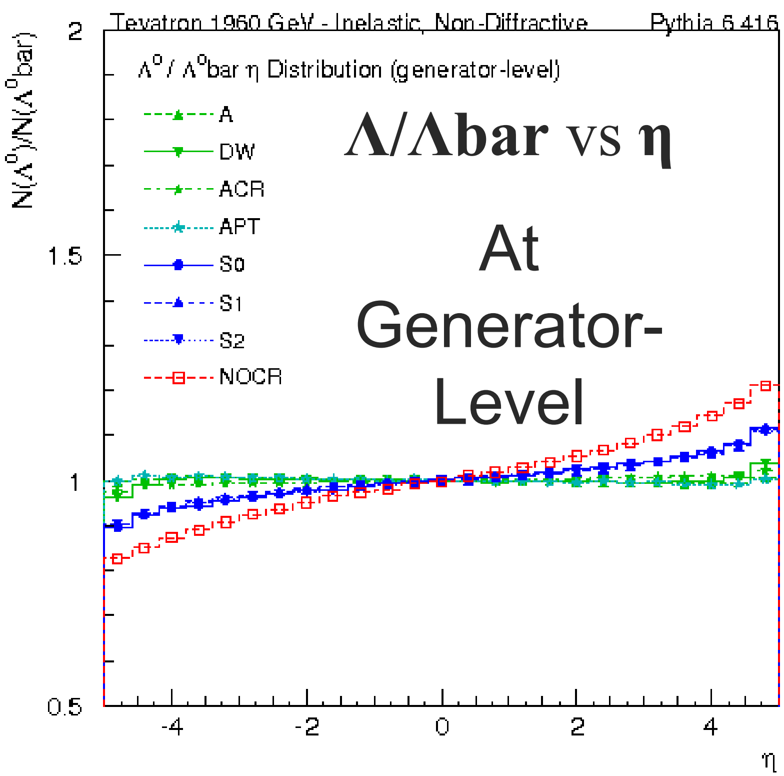


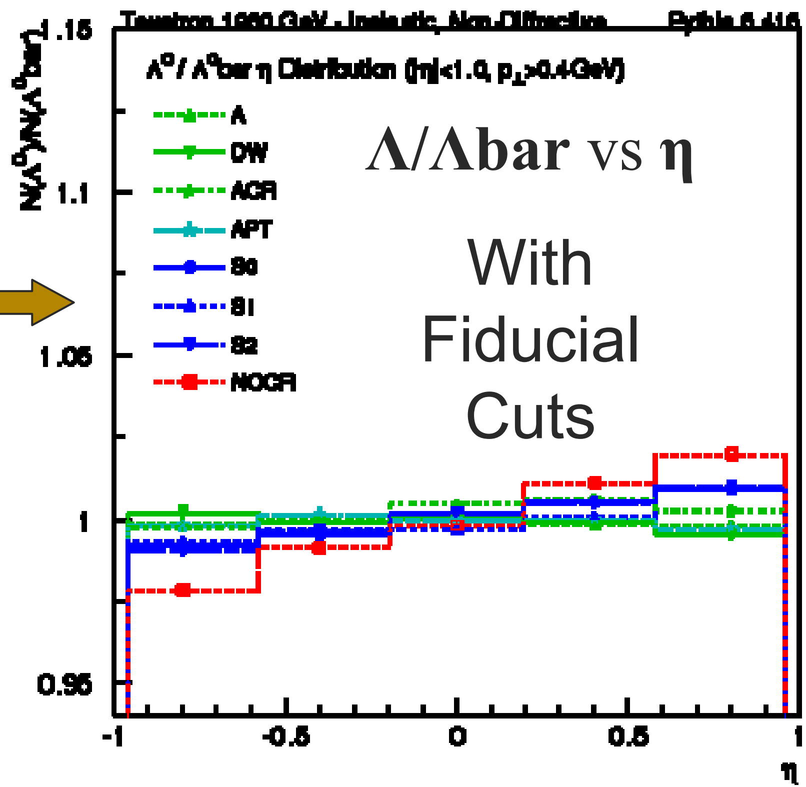

The manner in which QCD vacuum fluctuations are expelled from the interior region of a baryon […]. The surface plot illustrates the reduction of the vacuum action density in a plane passing through the centers of the quarks. The vector field illustrates the gradient of this reduction. The positions in space where the vacuum action is maximally expelled from the interior of the proton are also illustrated, exposing the presence of flux tubes. A key point of interest is the distance at which the flux-tube formation occurs. […] indicates that the transition to flux-tube formation occurs when the distance of the quarks from the centre of the triangle (< r >) is greater than 0.5 fm. The average inter-quark distance (< d >) is also indicated. Again, the diameter of the flux tubes remains approximately constant as the quarks move to large separations. As it costs energy to expel the vacuum field fluctuations, a linear confinement potential is felt between quarks in baryons as well as mesons.

[from http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/ ]

# ➔ Baryon Number Transport

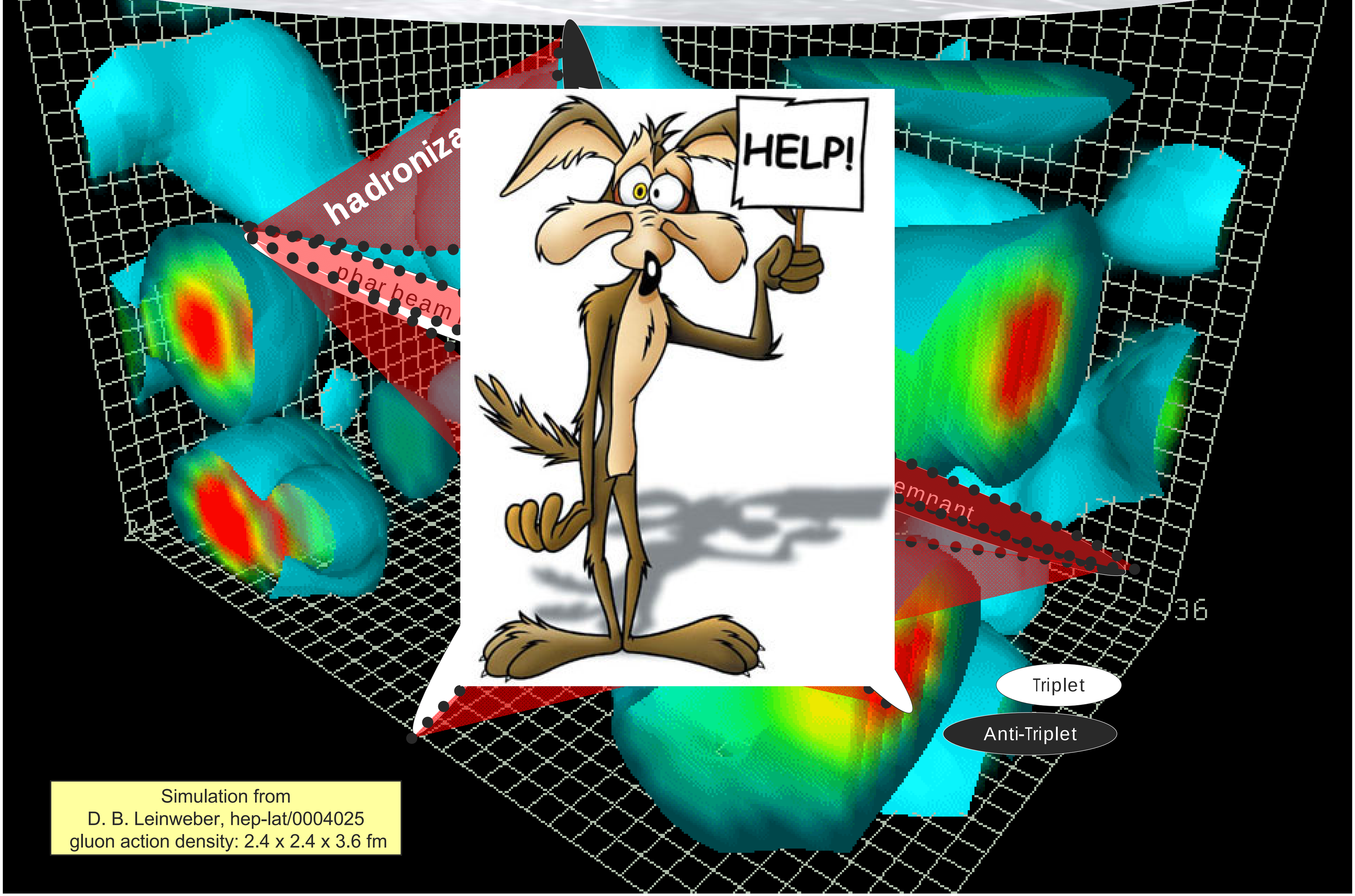
- Observable consequence




http://home.fnal.gov/~skands/leshouches-plots/

# Now Hadronize This

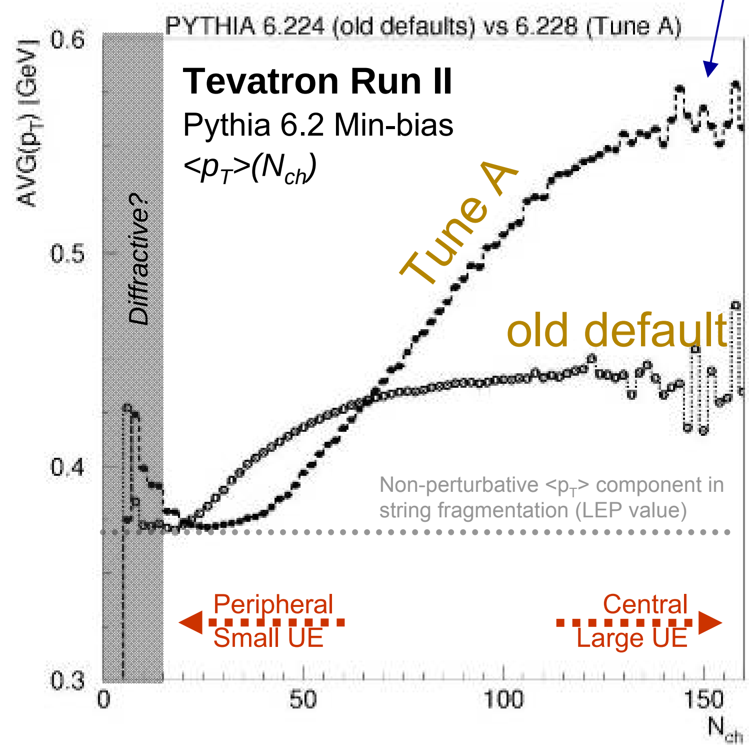



Simulation from
D. B. Leinweber, hep-lat/0004025
gluon action density: 2.4 x 2.4 x 3.6 fm

# Underlying Event and Color 2

- Min-bias data at Tevatron and RHIC showed a surprise
  - Charged particle pT spectra were highly correlated with event multiplicity: **not expected**
  - For his 'Tune A', Rick Field noted that a high correlation in color space between the different MPI partons could account for the behavior
  - But needed ~ 100% correlation. So far not explained
  - Virtually all 'tunes' now employ these more 'extreme' correlations
    - But existing models too crude to access detailed physics
  - What is their origin? Why are they needed?

Not only more (charged particles), but each one is harder



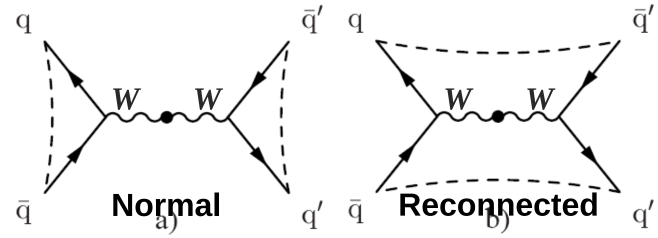

Successful models: string interactions (area law)

PS & D. Wicke : EPJC52(2007)133 ; J. Rathsman : PLB452(1999)364

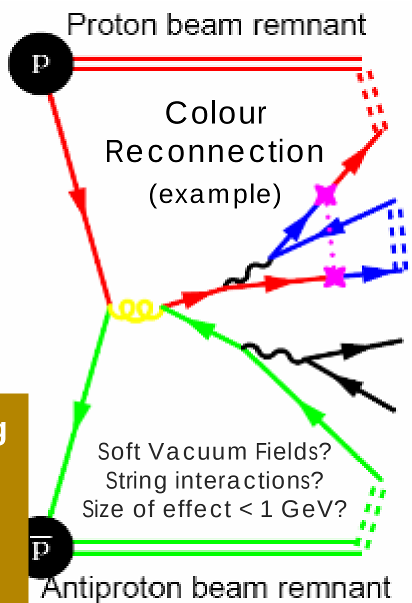
# Color **Re**-connections

Sjöstrand, Khoze, Phys.Rev.Lett.72(1994)28 & Z. Phys.C62(1994)281 + more …
**OPAL**, Phys.Lett.B453(1999)153 & **OPAL**, hep-ex0508062

- ► Searched for at LEP
  - Major source of W mass uncertainty
  - Most aggressive scenarios excluded
  - But effect still largely uncertain $P_{reconnect}$ ~ 10%




- ► Prompted by CDF data and Rick Field's studies to reconsider.
  What do we know?
  - Non-trivial initial QCD vacuum
  - A lot more colour flowing around, not least in the UE
  - String-string interactions? String coalescence?
  - Collective hadronization effects?
  - More prominent in hadron-hadron collisions?
  - What (else) is RHIC, Tevatron telling us?
  - *Implications for precision measurements:Top mass? LHC?*




Existing models only for WW ➔ a new toy model for all final states: **colour annealing**
Attempts to minimize total area of strings in space-time (similar to Uppsala GAL)
PS, Wicke EPJC52(2007)133 ;
Preliminary finding Delta(mtop) ~ 0.5 GeV
Now being studied by Tevatron top mass groups

Pythia

# Color Annealing

- Use String Area Law

Sandhoff + PS, in Les Houches ’05 SMH Proceedings, hep-ph/0604120

- → Toy model of non-perturbative color reconnections, applicable to any final state
  - Each string piece gets a probability to interact with the vacuum / other strings:

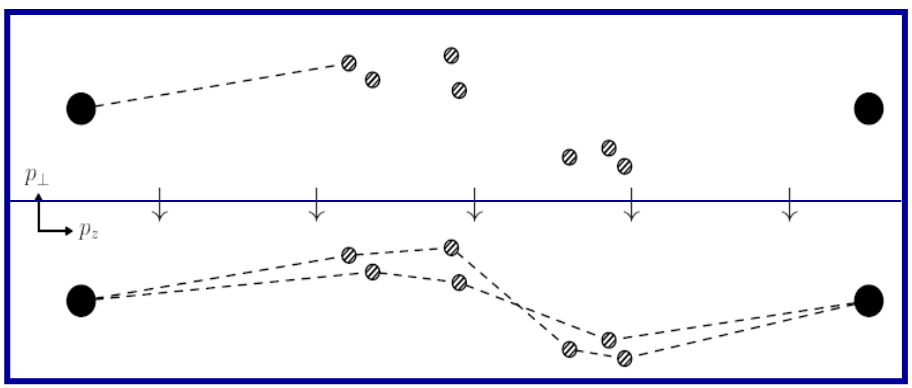
$$P_{\text{reconnect}} = 1 - (1-\chi)^n$$

  - $\chi$ = strength parameter: fundamental reconnection probability (free parameter)
  - n = # of multiple interactions in current event ( ~ counts # of possible interactions)

- For the interacting string pieces:

- New string topology determined by annealing-like minimization of ‘Lambda measure’ ~ potential energy ~ string length ~ log(m) ~ N
  - Similar to area law for fundamental strings: Lambda

$$\Lambda = \Pi_{i=1}^{N} \frac{m_i^2}{M_0^2}$$




►→ good enough for order-of-magnitude

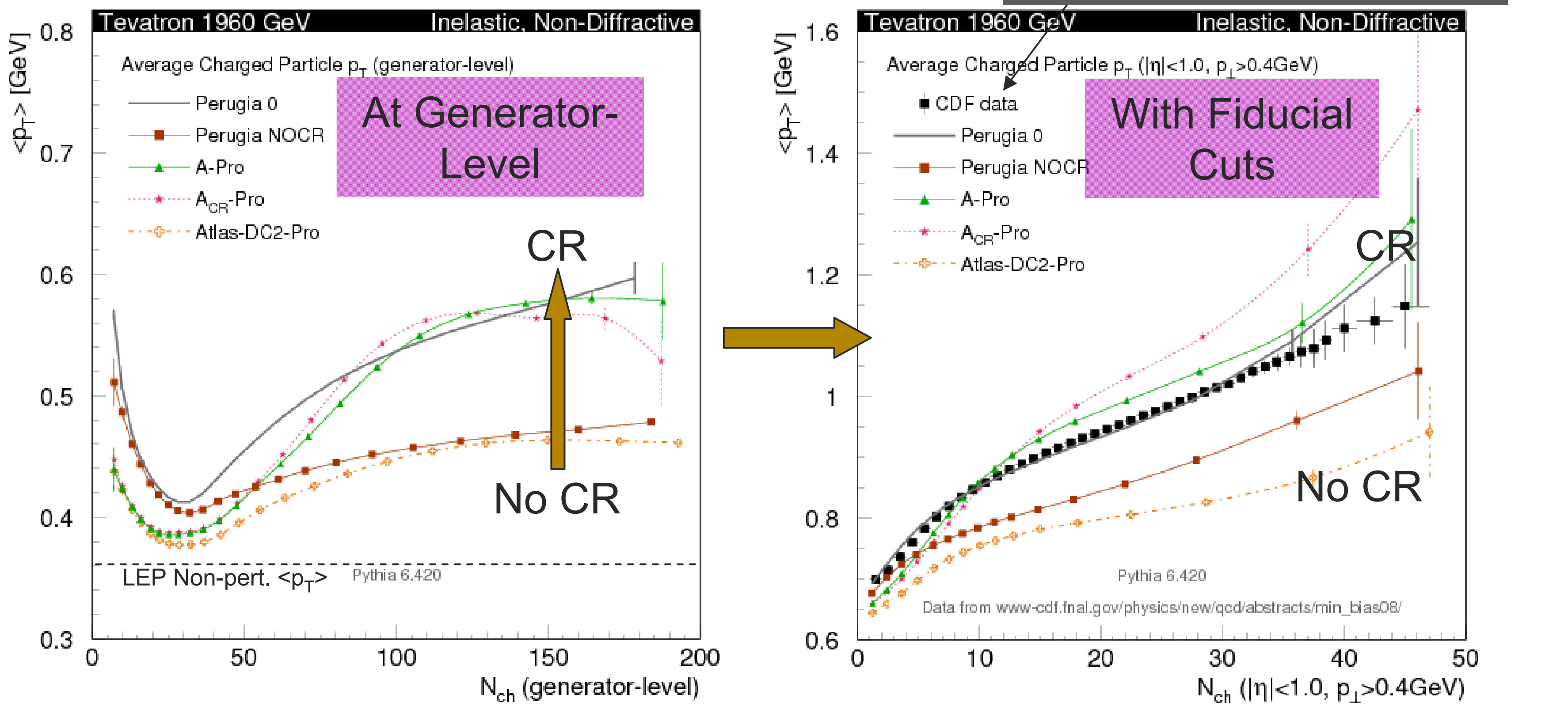
# Evidence for String Interactions?

- Tevatron min-bias

Pythia

Only the models which include *some* minimization mechanism for the string potential give good fits

Data courtesy of N. Moggi, Bologna

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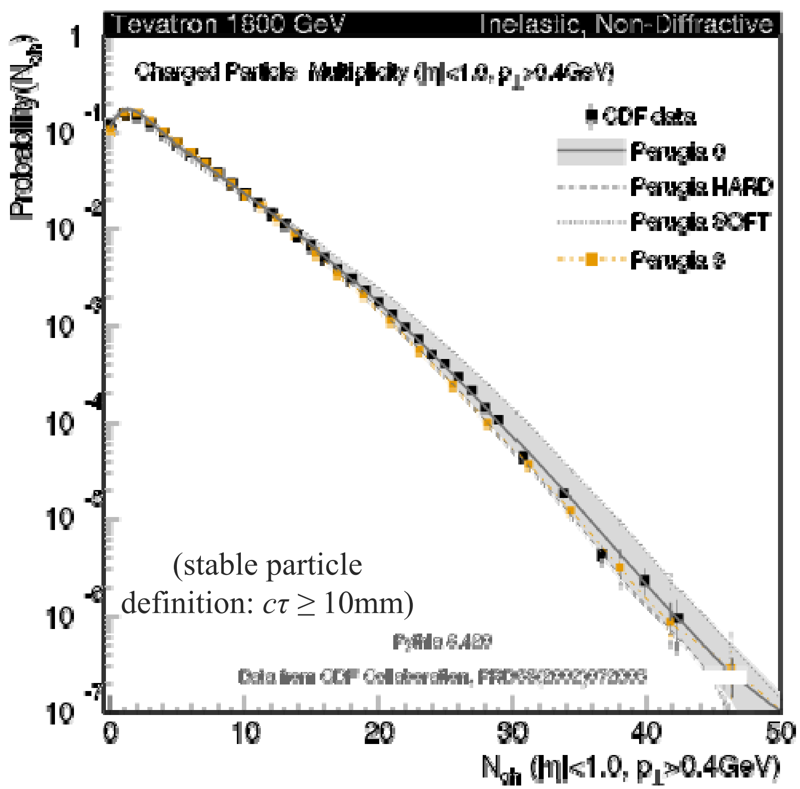
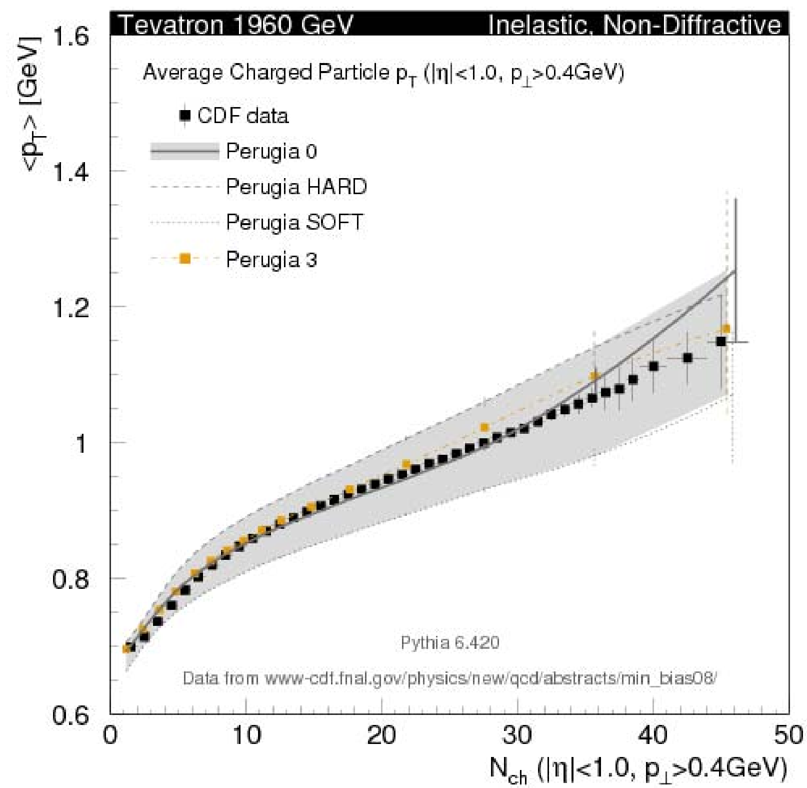
# Perugia Models

- Huge model building and tuning efforts by many groups (Herwig, Professor, Pythia, Sherpa, … )
  - Summarized at a recent workshop on MPI in Perugia (Oct 2008)
  - For Pythia (PYTUNE), 6.4.20 now out ➔ “Perugia” and “Professor” tunes
  - Scaling to LHC much better constrained, HARD/SOFT, + CTEQ6, LO*
    - **TeV-1960, TeV-1800, TeV-630, (UA5-900, UA5-546, UA5-200)**



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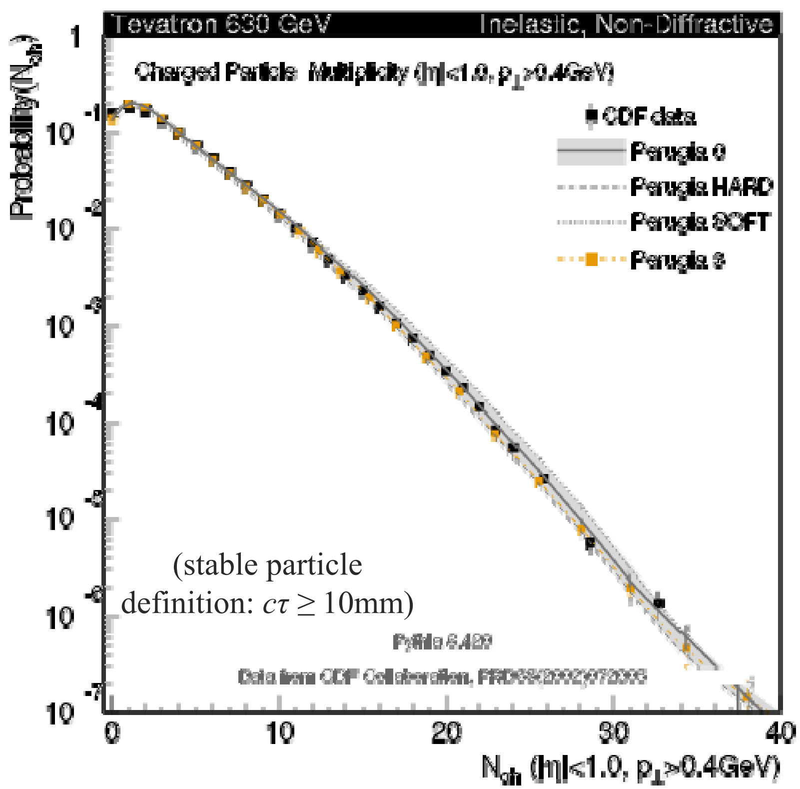


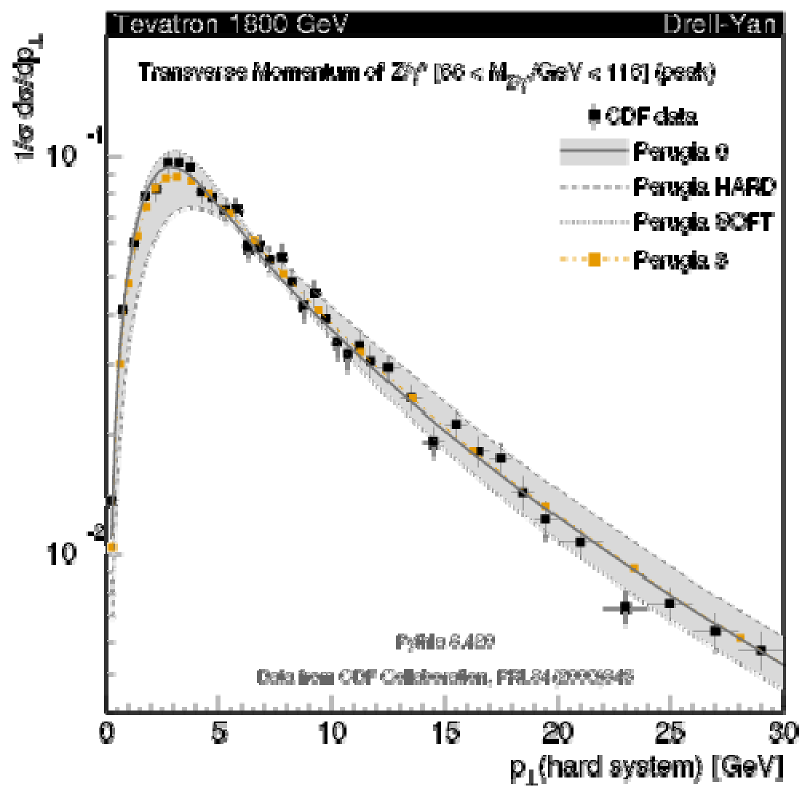

# (CTEQ6 and LO*)

- Huge model building and tuning efforts by many groups (Herwig, Professor, Pythia, Sherpa, … )
  - Summarized at a recent workshop on MPI in Perugia (Oct 2008)
  - For Pythia (PYTUNE), 6.4.20 now out ➔ “Perugia” and “Professor” tunes
  - Scaling to LHC much better constrained, HARD/SOFT, + CTEQ6, LO*
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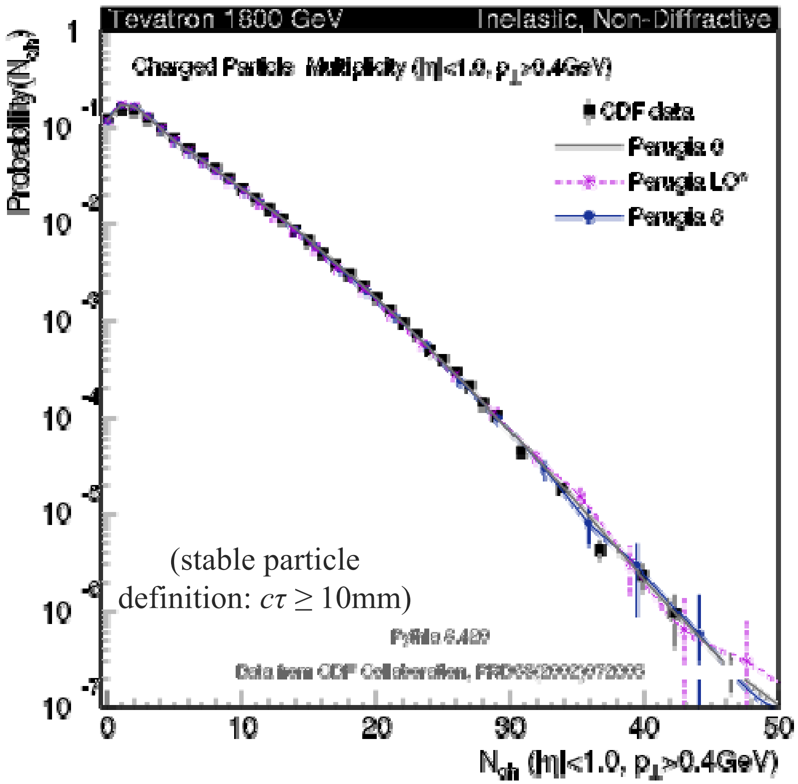


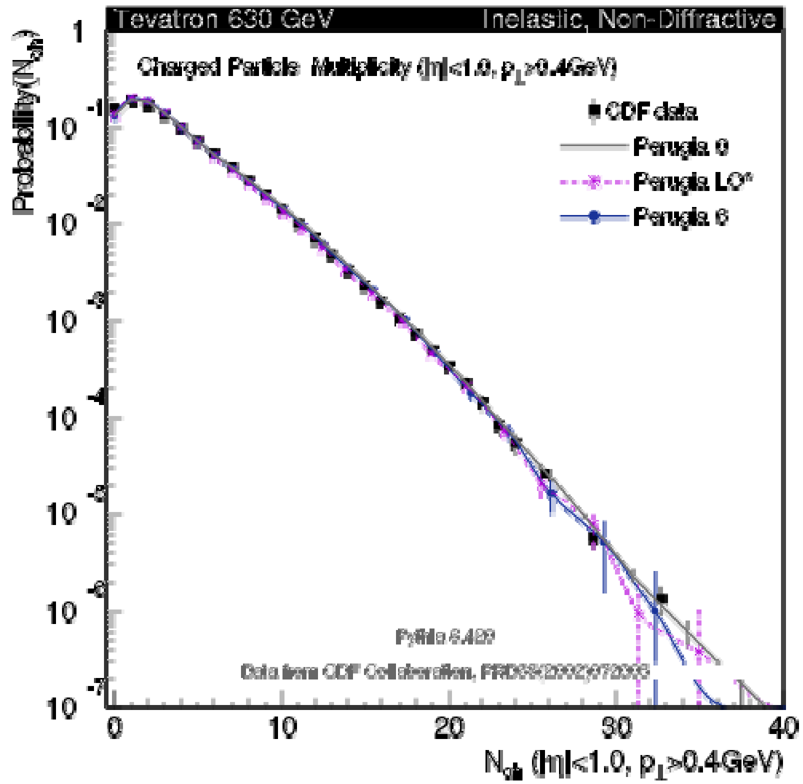

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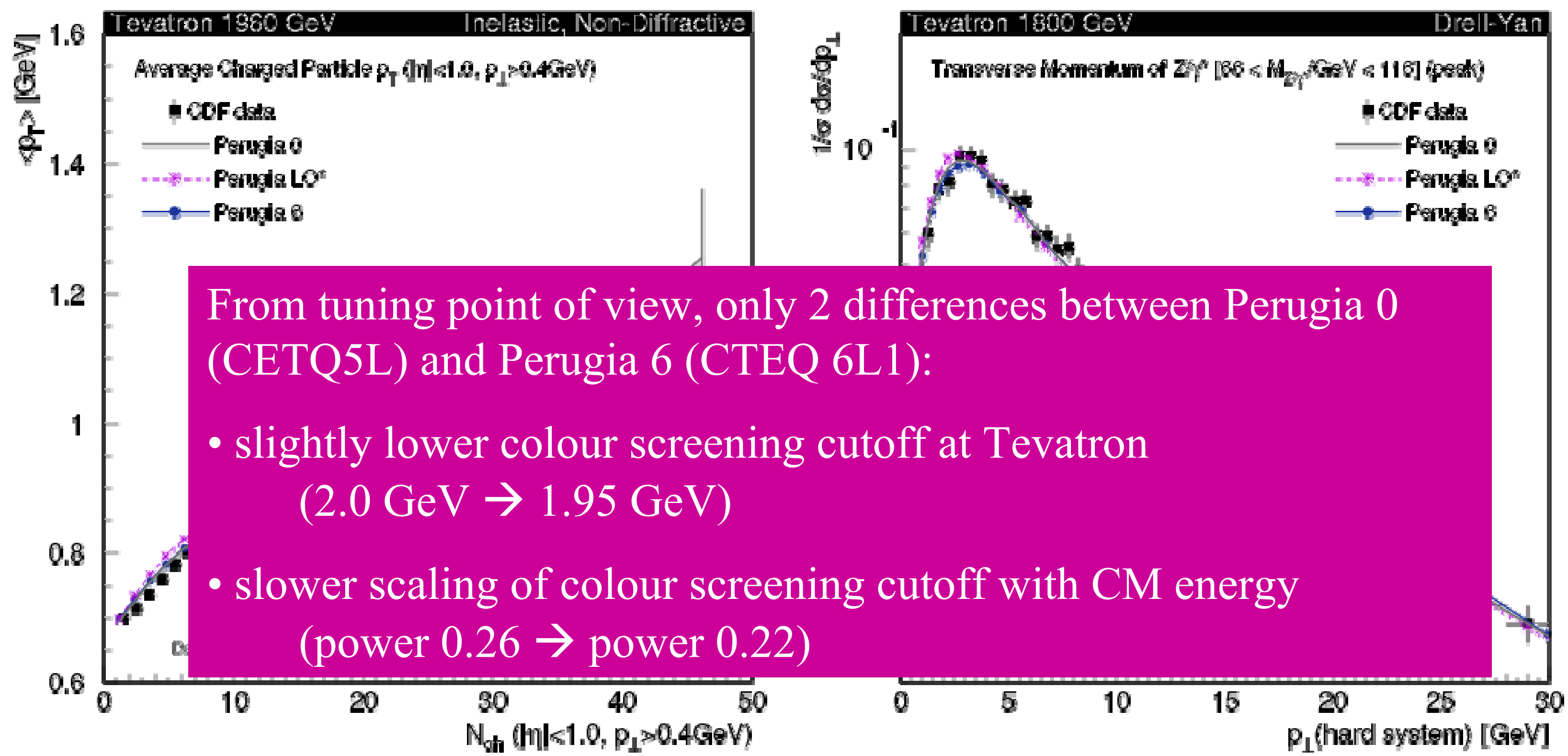
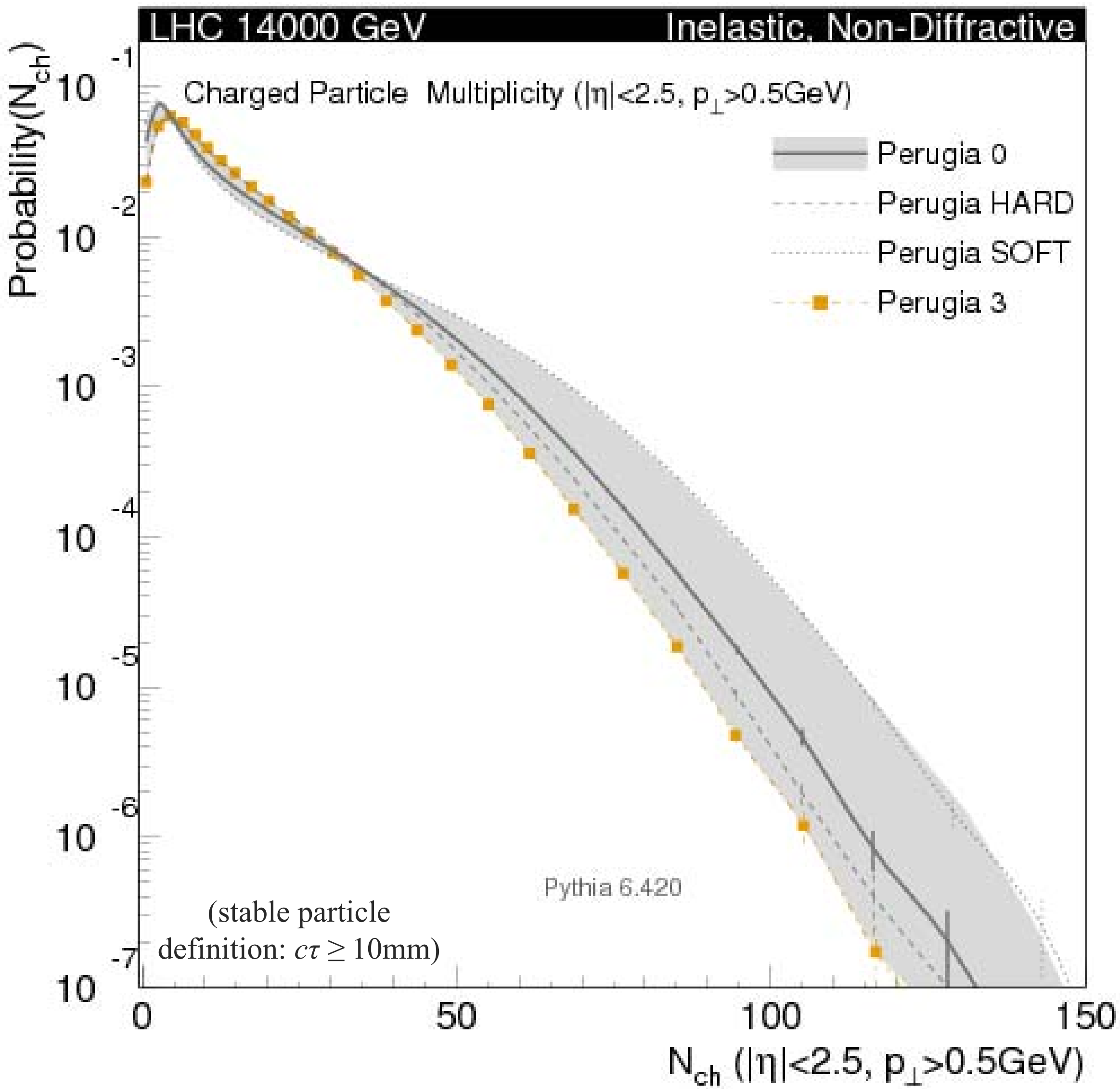



From tuning point of view, only 2 differences between Perugia 0 (CETQ5L) and Perugia 6 (CTEQ 6L1):

- slightly lower colour screening cutoff at Tevatron (2.0 GeV → 1.95 GeV)
- slower scaling of colour screening cutoff with CM energy (power 0.26 → power 0.22)

# Perugia Models




**→ Aspen Predictions:**

$|\eta| < 2.5$

$p_T > 0.5$ GeV

LHC **10 TeV** (min-bias)

**$\langle N_{tracks} \rangle = 12.5 \pm 1.5$**

LHC **14 TeV** (min-bias)

**$\langle N_{tracks} \rangle = 13.5 \pm 1.5$**

$1.8 < \eta < 4.9$

pT > 0.5 GeV

LHC **10 TeV** (min-bias)

**$\langle N_{tracks} \rangle = 6.0 \pm 1.0$**

LHC **14 TeV** (min-bias)

**$\langle N_{tracks} \rangle = 6.5 \pm 1.0$**

# Conclusions

# Questions

- Transverse hadron structure
  - How important is the assumption f(x,b) = f(x) g(b)
  - What observables could be used to improve transverse structure?
- How important are flavour correlations?
  - Companion quarks, etc. Does it really matter?
  - Experimental constraints on multi-parton pdfs?
  - What are the analytical properties of interleaved evolution?
  - Factorization?
- “Primordial kT”
  - (~ 2 GeV of pT needed at start of DGLAP to reproduce Drell-Yan)
  - Is it just a fudge parameter?
  - Is this a low-x issue? Is it perturbative? Non-perturbative?

# More Questions

- Correlations in the initial state
  - Underlying event: small $p_T$, small x ( although $x/X$ can be large )
  - Infrared regulation of MPI (+ISR) evolution connected to saturation?
  - Additional low-x / saturation physics required to describe final state?
  - Diffractive topologies?
- Colour correlations in the final state
  - MPI → color sparks → naïvely lots of strings spanning central region
  - What does this colour field do?
  - Collapse to string configuration dominated by colour flow from the "perturbative era"? or by "optimal" string configuration?
  - Are (area-law-minimizing) string interactions important?
  - Is this relevant to model (part of) diffractive topologies?
  - What about baryon number transport?
    - Connections to heavy-ion programme

# Multiple Interactions → Balancing Minijets

- Look for additional balancing jet pairs "under" the hard interaction.

- Several studies performed, most recently by Rick Field at CDF → 'lumpiness' in the underlying event.

(Run I)

**CDF**: Extraction by comparing double parton scattering (DPS) to a mix of two separate scatterings. Sample: 14000 $\gamma/\pi^0 + 3j$ events.

Strong signal observed, 53% DPS

angle between 2 'best-balancing' pairs